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14. ABSTRACT

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15. SUBJECT TERMS

Single-event upset, laser testing, two-photon absorption, threshold LET, heavy-ion testing, hardness assurance

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Direct Comparison of Charge Collection in SOI Devices from Single-Photon and Two-Photon Laser Testing Techniques

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Abstract—The amounts of charge collection by single-photon absorption (SPA) and by two-photon absorption (TPA) laser testing techniques have been directly compared using specially made SOI diodes. For SPA measurements and some TPA measurements, the back substrates of the diodes were removed by etching in XeF_2. With the back substrates removed, the amount of TPA induced charge collection could be correlated to the amount of SPA induced charge collection. However, the amount of TPA induced charge collection for diodes with substrates did not correlate to the amount of SPA induced charge collection with the substrates removed. Part of this difference may be due to displacement currents generated in the TPA SOI diodes with the back substrate present. The laser spot size may also affect the correlation between TPA and SPA induced charge collection measurements. These results illustrate the complexity of interpreting TPA and SPA single-event upset measurements.

Index Terms - Single-event upset, laser testing, two-photon absorption, threshold LET, heavy-ion testing, hardness assurance

I. INTRODUCTION

Single photon absorption (SPA) from the top of an IC and two photon absorption (TPA) from the back substrate can be used to characterize the single event effect properties of ICs [1], [2]. Both of these techniques have advantages and disadvantages compared to each other [2]. Little work has been been performed directly comparing the charge collection induced in an IC by these two techniques.

Previous works have suggested that laser pulse energy can be correlated to effective ion SEU threshold LET for SOI devices for both SPA and TPA [3]–[6]. For example, for top-side SPA laser irradiations, conversion factors of between 1 to 3 pJ (laser pulse energy) per 1 MeV-cm^2/mg (heavy-ion

LET) have been suggested [5], [7]. Similarly, for back-side TPA measurements, recent results have suggested a conversion factor of approximately 1 nJ^2 (laser pulse energy squared) per 1 MeV-cm^2/mg (heavy-ion LET) [6]. These works suggest that one should be able to quantitatively correlate SPA charge collection directly to TPA charge collection. However, this has not been explicitly shown.

In [6], it was also shown that the empirical relationship derived correlating heavy-ion threshold LET to TPA laser pulse energy for one SRAM did not yield accurate values of heavy-ion threshold LET based on laser pulse energy measurements for other SRAMs, including SRAMs built in the same device technology. This result suggests that the nature of charge collection induced by TPA may be more complex than originally believed [2], [8]. Clearly, more work needs to be performed to understand the detailed mechanisms for TPA-induced charge collection.

In this work, we investigate SPA and TPA charge collection in specially made SOI diodes that can be irradiated from the back substrate. These diodes were fabricated using different metal overlayers. The silicon substrates of some of the diodes were also removed (down to the buried oxide). This enabled a direct comparison between charge collection by SPA and TPA with and without the silicon substrate. Differences in the amounts of charge collection and possible mechanisms for the differences are discussed.

II. EXPERIMENTAL DETAILS

A. Devices

Charge collection was measured on n$^+$/p diodes specially fabricated for charge collection studies. The diodes were fabricated in Sandia's CMOS7 SOI technology and packaged in 40-pin DIP packages. They contain different combinations of AlCu metal overlayers with tungsten plugs as might be used in a high density IC. Up to five layers of tungsten/metallization are possible in this technology. For this work, we only examine the response in diodes with two different types of overlayers. Data are presented for diodes with only silicide above the active n$^+$ layers (referred to as silicide only) and for silicided n$^+$ layers plus tungsten plugs and metal 1 (referred to as contact + M1). Cross sections of these diodes are given in Figure 1. The top silicon layer is 250 nm thick and the
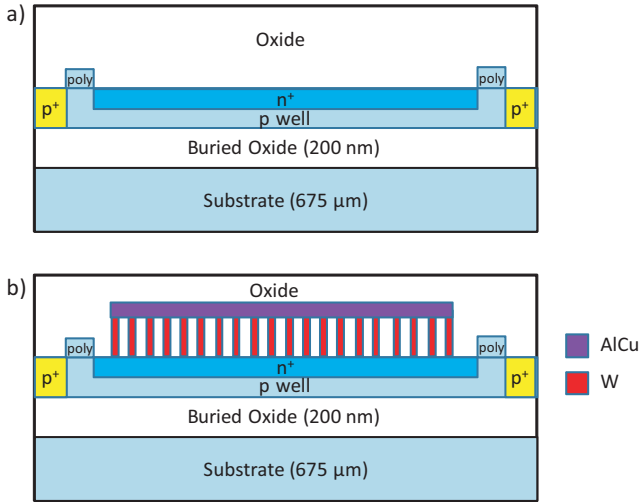
Fig. 1. Cross section of the diodes used for charge collection measurements: a) silicided n^+ layers (silicide only) and b) silicided n^+ layers plus tungsten and metal 1 (contact + M1). Diodes with the back substrate removed were also used.
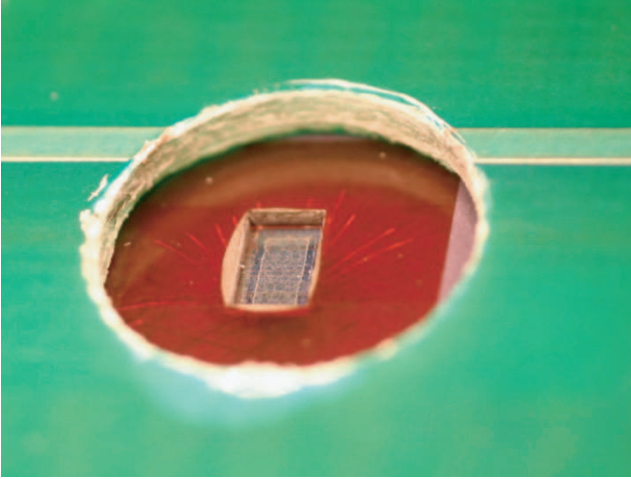

Fig. 2. Back surface with the substrate removed using XeF_2.

n+ layer extends approximately 125 nm into the top silicon layer. The buried oxide and bottom substrate thicknesses are approximately 200 nm and 675 μm, respectively. Contacts to the n^+ and p^+ regions are made at the edge of structures (next to the poly; contacts not shown in Figure 1). These regions are silicided for making good contacts. The total diode area is ~400 × 600 μm and the contact area is a small fraction of the total diode area. The backsides of the diodes were polished at the wafer level.

For some devices, the back substrates were also removed down to the buried oxide using a XeF_2 etch. The process developed in this work to remove the backside is similar to that developed in [9]. A photograph of the bottom of the PC board with the back silicon etched is given in Figure 2.

In another approach, the backs of the packages were first milled and then back-side polished die were epoxy bonded to the milled packages. After that, the tops of the packages were filled with non-conducting epoxy and the back substrates were etched in XeF_2. These packages were then mounted on PC

boards, which also had holes milled out to expose the back surfaces of the devices. This approach avoided problems with cracking associated with the grinding process. There were no apparent deleterious effects of this approach on the electrical performance of ICs [9].

B. Laser Exposures

All laser exposures were performed from the backside of the diodes using picosecond or femtosecond laser pulses. Details of the TPA setup and technique have been discussed previously [2], [8]. The wavelength of the subbandgap laser pulses was approximately 1.26 μm. The pulse width of the TPA laser pulses is 120 fs. The optical pulses were focused onto the backsides of the diodes with a 100 × microscope objective, resulting in a near-Gaussian profile with a full-width-at-half maximum diameter of 1.6 μm at focus. The repetition rate of the laser pulses was 1 kHz. The wavelength of the SPA laser pulses was 590 nm. The pulse width of the SPA laser pulses is 1 ps. The SPA optical pulses were also focused onto the backsides of the diodes with a 100 × microscope objective resulting in a near-Gaussian FWHM diameter of approximately 1 μm. The repetition rate of the laser pulses was 12 kHz.

C. Charge Collection Measurements

Charge collection was measured by connecting the diode to an AMPTEK CoolFET charge sensitive preamplifier with a nominal gain of 4 V/pC. The preamplifier signal was then connected to an Ortec 671 spectroscopy amplifier with a nominal gain of 5. The signals from the spectroscopy amplifier were measured using an AMPTEK MCA8000 multichannel analyzer. Also, in separate experiments, the spectroscopy amplifier's waveform was recorded using a digital oscilloscope. In this case, 500 waveforms were recorded, the signal was averaged, and the statistical uncertainties were calculated. All measurements were performed with a reverse bias of 3 V across the diode.

III. RESULTS

A. Comparison of SPA and TPA With the Back Substrate Removed

Figure 3 is a direct comparison of the charge collected for TPA and SPA measurements for silicide-only diodes with the back substrate removed. Both sets of measurements were performed with the laser pulses focused at a location close to one of corners of the rectangular diodes. For the TPA experiments, the square of the laser pulse energy is plotted. The square of laser pulse energy is plotted because of the "two-photon" nature of these tests. (One electron/hole pair is generated for every two photons absorbed [10].) The TPA and SPA energy scales have been arbitrarily adjusted to match the TPA and SPA charge collection results. The curves roll over with increasing laser pulse energy, i.e., a smaller fraction of the charge is collected at high incident laser energy than is collected at lower incident pulse energies. This is likely due to nonradiative recombination. This "saturation effect" is
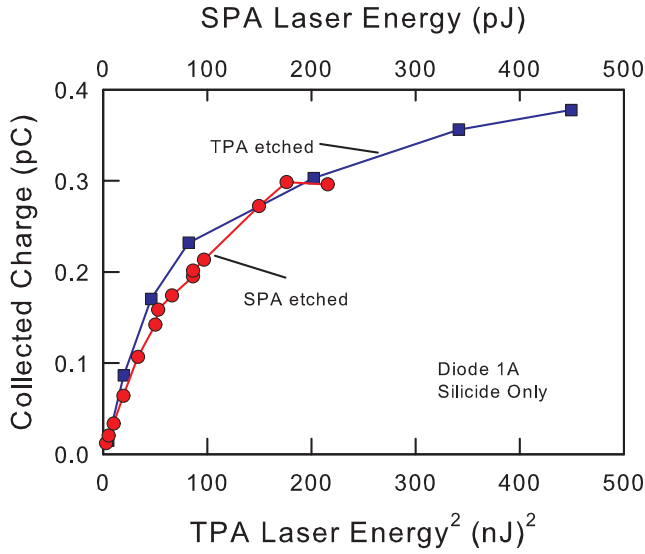
Fig. 3. Comparison of the charge collected from silicide-only diodes for TPA and SPA measurements. The back substrate was removed for both the TPA and SPA measurements.

Fig. 4. The effect of laser spot size for SPA charge collection measurements for silicide-only diodes.

common in optical devices. These data show that the increase in collected charge with SPA laser energy is qualitatively consistent with the increase in charge collection with TPA laser energy squared. This is the first experimental demonstration of this.

To quantitatively compare the TPA and SPA charge collection results, one can correlate the laser energy (or laser energy squared) to ion LET for both SPA and TPA. Note that the quantitative results will depend on numerous test parameters, and will vary from facility to facility as well as over time for a given facility. For example, for SPA, the laser wavelength and spot size could affect the correlation. For TPA, the laser wavelength, spot size, pulse width, and possibly the phase characteristics of the pulse could affect the correlation. The results reported here are generally valid only for the specific experimental conditions under which these experiments were performed. As a rule, nonlinear optical experiments are very difficult to perform quantitatively. The intent here is to show for a given set of experimental parameters whether or not TPA and SPA laser measurements can be quantitatively correlated. For SPA measurements, as noted above, previous works suggest that a SPA laser energy of 100 to 300 pJ corresponded roughly to a heavy-ion LET of 100 MeV-cm^2/mg [3], [4] for a given set of the experimental conditions. Similarly, for TPA measurements, previous works suggest a TPA laser energy squared of 100 nJ^2 corresponded roughly to a heavy-ion LET of 100 MeV-cm^2/mg [6] for another set of experimental conditions. If we assume a SPA laser conversion factor of 1 pJ for a heavy-ion LET of 1 MeV-cm^2/mg (as derived for a 50 nm SOI device with a 150 nm silicon thickness [5]), a SPA laser pulse energy of 100 pJ would be equivalent to a TPA laser energy squared of 100 nJ^2, and both should be equivalent to a heavy-ion LET of $\sim$100 MeV-cm^2/mg. We note from Figure 3 that the charge collection for a SPA laser pulse energy of 100 pJ is approximately equal to the charge collection for a TPA laser energy squared of 100 nJ^2. Hence, based on this
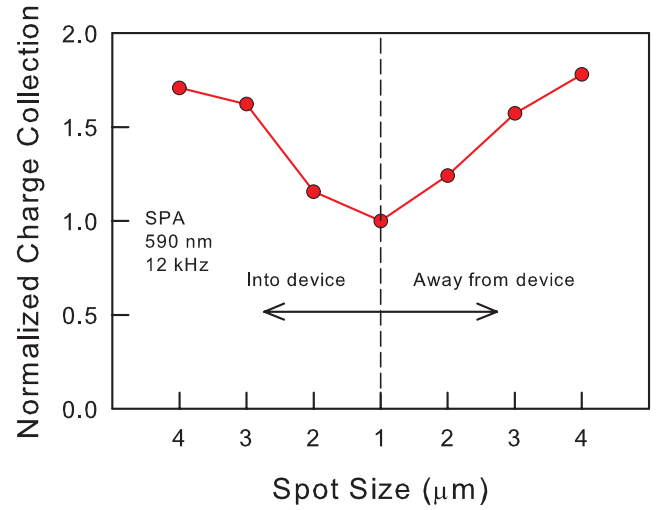
simplistic argument, the adjustment of SPA and TPA energy scales in Figure 3 appears to be consistent with previous work and indicates that quantitative correlations can be developed between TPA and SPA charge collection measurements. However, it must be noted that the TPA measurements in [6] were performed with the back substrate not removed. The previous SPA measurements [5] were taken from the top side and reflections and light attenuation from silicide layers and the polysilicon gates may have reduced the light intensity for the SPA measurements. To more accurately compare TPA and SPA charge collection measurements, TPA and SPA data correlating laser energy (or laser energy squared) to heavy-ion LET should be taken on ICs with the back substrate removed. Nevertheless, these results do show that there is reasonable quantitative agreement between the SPA and TPA charge collection results.

1) Focusing Effects: One large difference observed between SPA and TPA charge collection measurements was the effect of focusing of the laser light onto the diode. For the SPA measurements, a large focusing effect was observed. Figure 4 is a plot of collected charge versus laser spot size for SPA measurements on silicide-only diodes. Into the device refers to the diode being moved towards the microscope objective used to focus the laser light and away from the device refers to the diode being moved away from the microscope objective. As is evident in the figure, moving the diode either away from or towards the central point of focus increases the amount of charge collection. The amount of charge collection is nearly symmetric in either direction. Hence, the lowest amount of charge collection occurs when the laser spot size is optimally focused onto the diode. This is the exact opposite from what is observed in TPA experiments, where the focus is set by moving the device in the laser beam until charge collection is maximized.

The mechanism for this focusing effect for SPA measurements is not immediately obvious. The same amount of charge is deposited for each case; the observed effect is due solely to changes in the laser spot size and the density of deposited charge. The size of these diodes ($\sim$400 $\times$ 600 μm) is very

large compared to the laser spot size. Thus, the same number of photons are contributing to charge collection regardless of how the laser spot size is focused. One possible mechanism for this effect could be due to charge yield. As the laser light is focused more tightly onto the diode resulting in a smaller spot size, the separation of the electron/hole pairs generated by the laser light will be less. This could result in increased initial recombination. The high density of electron/hole pairs generated by the laser pulse could also contribute to collapse of the electric field. The extent of electric field collapse will also increase as the laser spot size decreases and it will also contribute to decreases in charge-yield [11], [12]. The effect of the electric field collapse will be most efficient away from the edges of the large area diodes of this study, and should be more effective at lower biases. As a result, fewer electron/hole pairs per incident photon will be able to contribute to charge collection as the laser light is focused to a smaller spot size. Regardless of the mechanism for this effect, these results show that SPA laser spot size could have a large impact on the correlation between SPA and TPA charge collection measurements and as a consequence, the SEU rate of an IC as measured by SPA and TPA. A test to show whether or not the focusing effect is caused by differences in charge yield could be to perform the same measurements parametrically as a function of energy. If the results are independent of laser pulse energy, then the argument for a recombination effect is unlikely. This will be investigated in future experiments.

2) Effects of Metal Overlayers: Charge collection was also investigated for diodes with different metal overlayers to determined if reflections from metal layers in the back-end-of-the-line process could increase the amount of charge collection. Figure 5 is a comparison of the charge collection for SPA measurements for silicide-only and contact + M1 diodes. (The contact + M1 diodes also have silicide.) All measurements were made with the substrates removed. The charge collection is actually less for the contact + M1 diodes than for the silicide-only diodes. Similar results were also obtained for TPA measurements for silicide-only and contact + M1 diodes with the substrates removed. These results may be more of an indication of the effect of metal overlayers on diode quality than on reflections from metal surfaces. For example, the metal overlayers may have retarded the diffusion of hydrogen into the silicon diodes during device processing. It has been shown that hydrogen diffusing into SOI capacitor structures during a low temperature anneal (e.g., 450°C) can passivate interface traps at the oxide/silicon interface leading to increased heavy-ion induced charge collection [13]. Also, the diode ideality factors (determined from the slope of exp(-qV/nkT) were different for the two diodes (n = 1.09 for the silicide only diodes and 1.27 for the contact + M1 diodes). This is also an indication of differences in the recombination properties of the two diodes.

B. Comparison of TPA With and Without the Back Substrate

1) Reflections: The results presented above are for data taken with the substrate removed. Normally, the back substrate is present in TPA experiments, and this can affect the amount
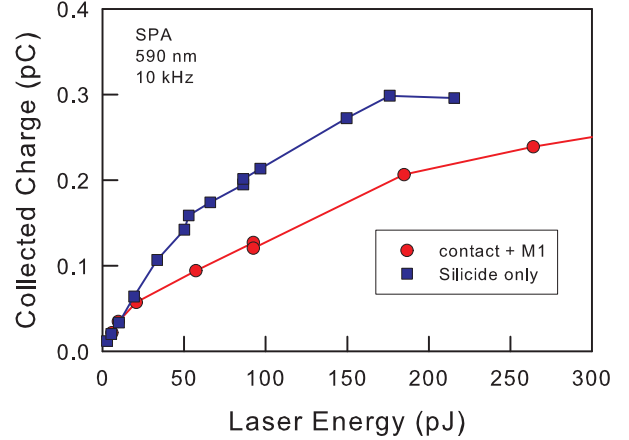

Fig. 5. Comparison of the charge collected from silicide-only diodes and contact + M1 diodes for SPA measurements. The back substrate was removed for both measurements.

of charge collection observed. Figure 6 is a plot of charge collection versus the square of the laser pulse energy for the silicide-only diodes with and without the substrate removed. The TPA data for the etched substrates is taken from Figure 3. Both sets of measurements were performed with the laser pulses focused at approximately the same location close to edges of the diodes (as will be shown below, the location of the TPA laser measurements for the non-etched substrates can affect the amount of charge collection). Significantly more charge collection is measured with the substrate removed than with it present.

One possible cause for the reduction in charge collection for diodes with the substrate present is reflections by the back substrate. For an optically flat surface, with the substrate present, the amount of reflection loss at the air/substrate and substrate/buried oxide interface can be calculated from Fresnel's equations [14]. They add up to approximately a 42% reflection loss; whereas, with the substrate removed, the air/buried oxide interface gives only about a 4% reflection loss. However, in combination, the air/buried oxide/silicon (without the substrate) and air/silicon/buried oxide/substrate stacks form plane-parallel etalons and multiple reflections from the partially reflecting dielectric interfaces of the etalon will occur. As a result, interference effects caused by the etalon structure may alter the net amount of light transmitted into the silicon active layer. Because the light transmitted into the silicon active layer will not be in phase (in general), interference effects caused by the multiple reflected light will decrease the laser pulse energy transmitted into the silicon active area. When etalon effects are taken into account, the net transmitted light into the silicon active layer for the air/buried oxide/silicon stack (without the substrate) is 48% and for the air/silicon/buried oxide/substrate stack is 39%. Thus, interference effects do not result in substantial differences in the amount of charge collection for didoes with and without the back substrate. As is also shown in Figure 6, to actually match the data, the laser energy for the TPA measurements with the substrate present must be adjusted by 60%. This is well above the amount
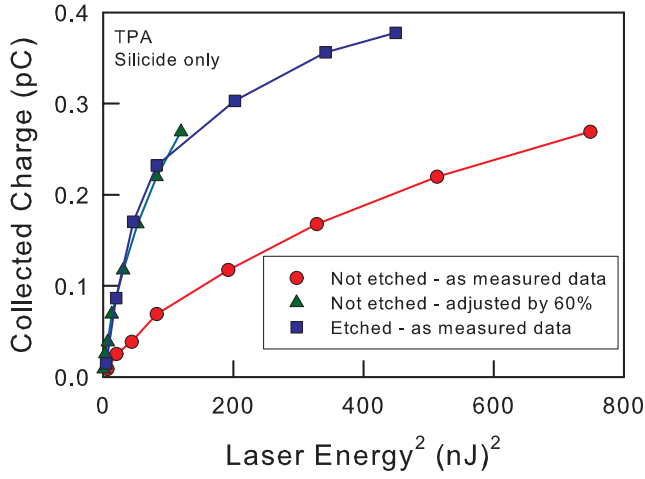
Fig. 6. Comparison of the charge collected from silicide-only diodes with and without the substrate removed for TPA measurements.
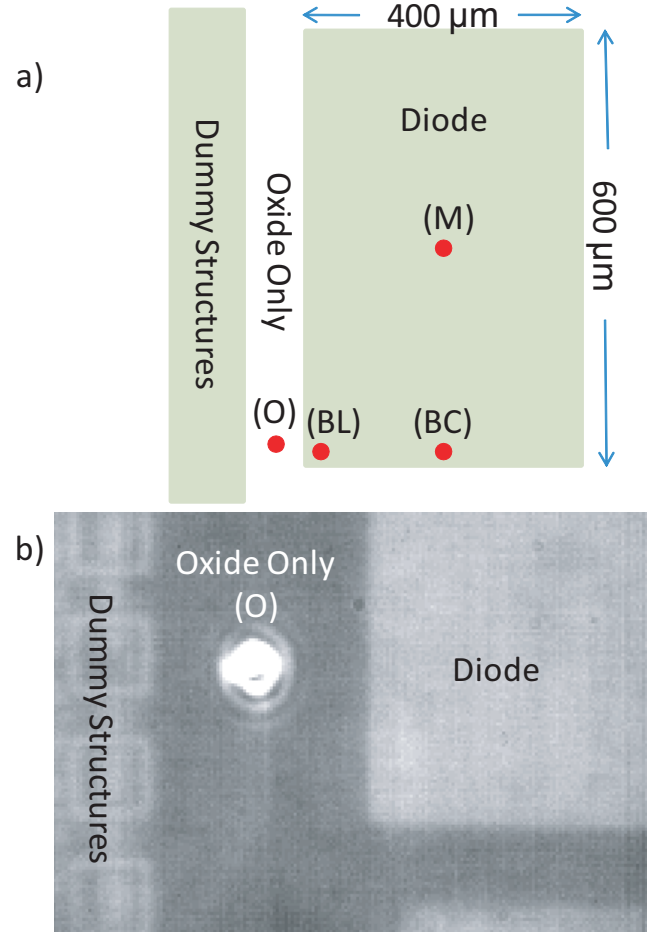

Fig. 7. Locations on and off the diode where charge collection was measured: a) actual locations and b) photograph of the laser light over an oxide only area.
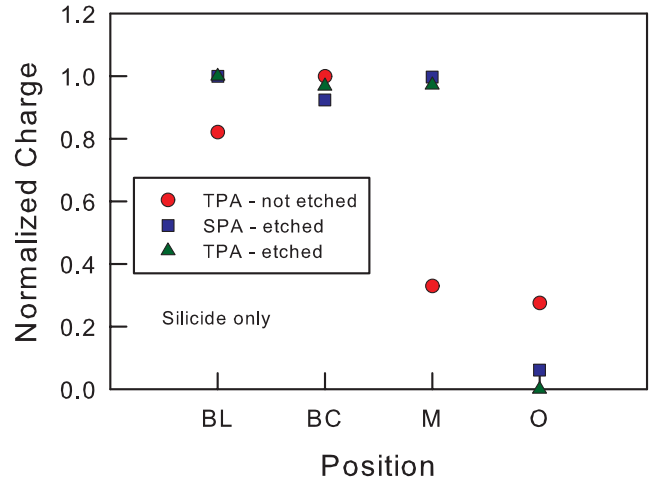

Fig. 8. Charge collection for SPA measurements without the substrate and TPA with and without the substrate at different locations on and outside the diode. All measurements were made on silicide-only diodes.

that can result by differences in reflections. As will be shown below, the differences in charge collection may be associated with laser-induced displacements currents for diodes with the substrate present.

2) Spatial Effects - Displacement Currents: The amount of charge collection varied considerably with position for the TPA measurements with the substrate present. Diodes were exposed at different locations on and off the diode. The different locations are given in Figure 7. Figure 7a shows the approximate locations on and off the diode (bottom left (BL), bottom center (BC), and middle (M) on the diode and oxide only (O) off the diode). Figure 7b is a photograph of a magnified area showing the reflected laser light focused on an area off the diode (i.e., over an oxide only area).

The effect of laser position on charge collection is illustrated in Figure 8, which gives the normalized amount of charge collection for SPA measurements without the substrate and TPA measurements with and without the substrate at different locations over the diode and over oxide areas outside of the diode (there are no silicon or metal layers over the buried oxide in these regions). Each data set was normalized to its maximum value for the four different positions. The SPA and TPA charge collection measurements on diodes without the substrate are consistent with expected results. There is little to no difference in charge collection at different locations over the diode and the charge collection drops to zero (within experimental uncertainty) over oxide areas outside of the diodes. However, charge collection for TPA measurements with the substrate present is conceptually different. Near the edges of the diodes (BL and BC; the locations of the TPA measurements for the data of Figures 3 and 6) the charge collection is maximum and does not vary significantly with location. However, near the center of the diode (M), the amount of charge collection is only one third of what it is at maximum near the edge of the diode. In addition, the amount of charge collection over oxide areas outside of the diode (O) is significant and almost equal to that of the charge collection over the center of the diode!

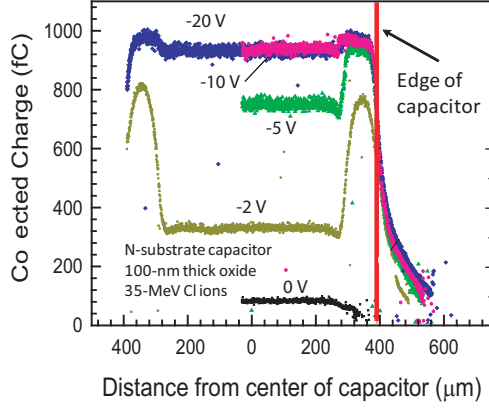These results are very reminiscent of heavy-ion microbeam

Fig. 9. Heavy-ion induced charge collection in SOI capacitors for different bias voltages versus position along the capacitor. Taken from [15].

results taken on SOI capacitors, which showed that significant displacement currents can be induced by ion strikes in the back substrate resulting in charge collection in the top silicon layer [15]. This is illustrated in Figure 9, which is taken from [15]. Similar to an ion strike, immediately after the laser pulse, charge generated in the substrate will change the potential at the substrate/oxide interface. This change in potential generates a displacement current, I_D (I_D = C dV/dt). This displacement current lasts for several nanoseconds (until the charge in the substrate diffuses away and the original depletion region is reformed). Because displacement currents are created by charge generation in substrate, large differences in charge collection could occur for SPA and TPA measurements without the substrate and TPA measurements with the substrate.

Similar to Figure 8, the maximum amount of heavy-ion induced charge collection occurs when the ion beam is focused over silicon but near the edge of the capacitor. The amount of charge collection is considerably reduced in the center of the capacitor (especially for low voltages). The increase in charge collection at the edges of the capacitor results from variations in the depletion region at the edges caused by a non-uniform distribution in trapped charge along the oxide/substrate interface [13]. Significant charge collection is also induced when the ion beam is focused over oxide only areas.

The impact of these displacement currents on TPA charge collection measurements and on single-event upset measurements on ICs, in general, needs to be determined. For example, it has been shown that for heavy ion irradiations charge collection in MOS elements strongly depends on the geometry, gate surface area and oxide thickness of the device [16]. In an IC, the amount of charge collection may be reduced at the struck node by charge sharing effects. Charge induced by displacement currents caused by the generation of charge in the substrate by an ion strike (laser pulse) may also be collected at adjacent circuit nodes (charge sharing), lessening the charge collection efficiency at the struck node. As a result, the drain regions of SOI technologies are not sensitive to charge released in the substrate. Their small surface area, together with the

relatively thick buried oxide, result in insignificant charge collection from displacement currents. Whether or not this is also true for TPA SEU measurements remains to be shown. The relatively large spot size of the laser could potentially affect the charge collection efficiency at individual circuit nodes.

IV. SUMMARY

The charge collection due to SPA and TPA laser irradiations has been directly compared using specially made SOI charge collection diodes. For diodes with the substrates removed, the amount of SPA induced charge collection compares quantitatively to the amount of TPA induced charge collection. However, SPA laser spot size can greatly affect the correlation between TPA and SPA. While a direct comparison can be made for the etched devices, a direct comparison does not appear to be valid for the substrate/no substrate samples. Displacement current effects that are not present when the substrate is removed complicate interpretation of the data. The extent of these effects on charge collection in ICs is not clear. As a result, considerably more work needs to be performed before the correlation of SEU error rates in SOI ICs measured by TPA can be directly correlated to those measured by SPA.

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